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Title: Modeling Cosmic Rays in GEANT4

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Intended for: U.S. Fukushima Team meeting in Japan with TEPCO, KEK, and others related to Fukushima

Modeling Cosmic Rays in GEANT4

Borozdin K., Bacon J., Milner E., Miyadera H., Morris C., Perry J.

For US Fuku Team

5月23ー24日のミューオン会議

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Components of GEANT4 Model

- Cosmic-Rays
- Detectors
- Reactor building

understand and remove

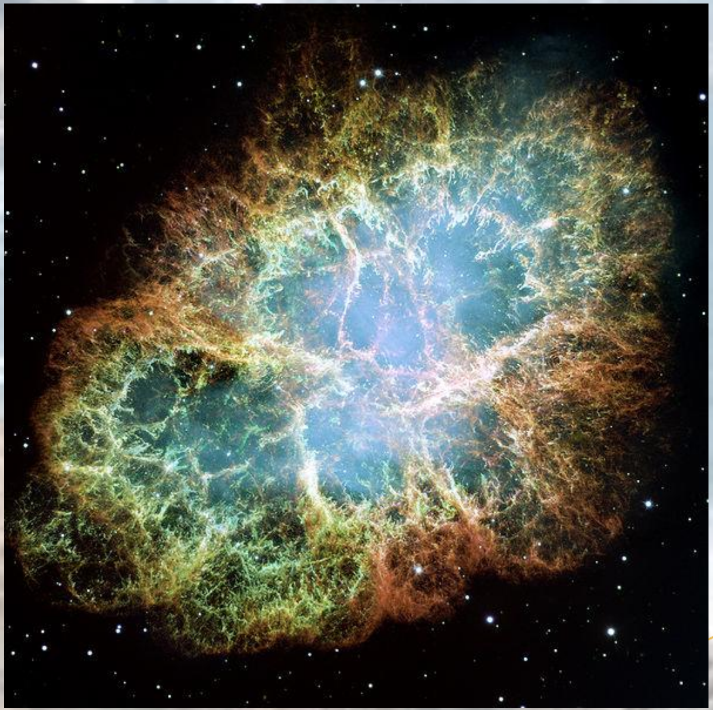
- Fuel ➔ measure

Cosmic Rays: Where Do They Come From?

- Discovered by Victor Hess in 1912
- Consist of mainly protons, electrons, and ions
- Ray acceleration can occur in strong magnetic fields from supernova blast wave remnants
- Energies range from MeV to beyond TeV

Victor Hess (1883 – 1964)

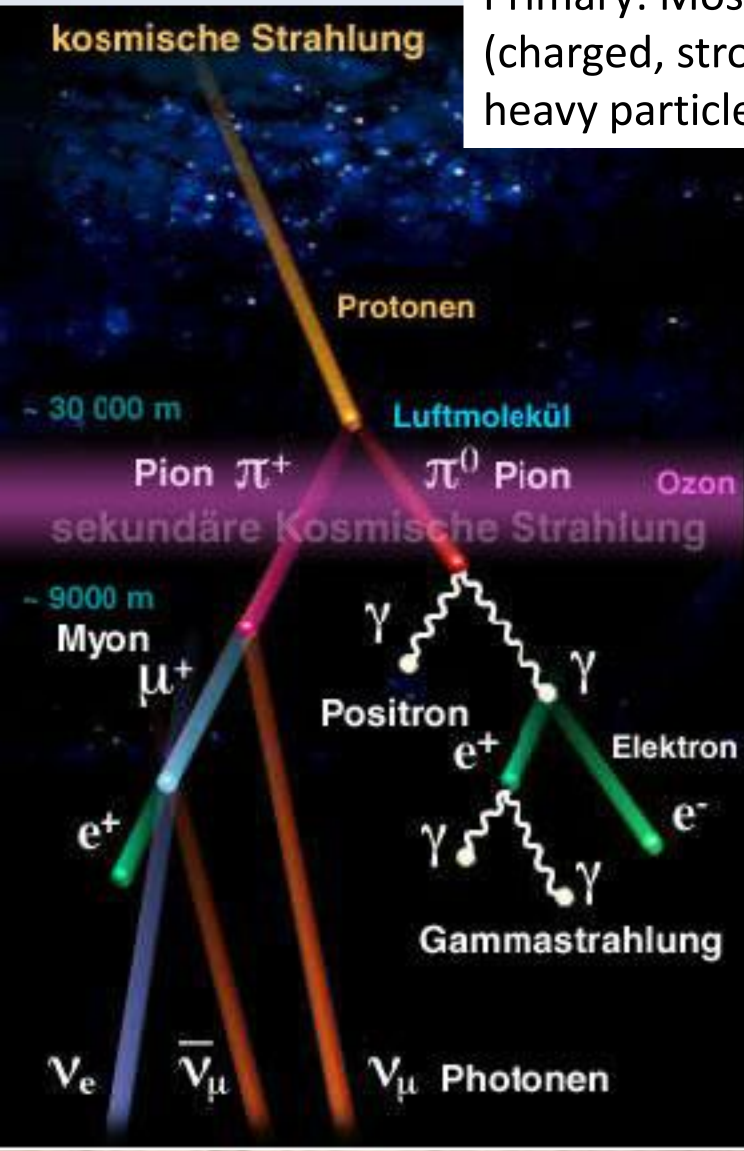
The Nobel Prize in Physics 1936



Crab Nebula (SNR 1054 remnant)

Cosmic Rays Conversion In Atmosphere

Primary: Mostly **protons** (charged, strongly interacting heavy particles, ~99%)



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Secondary:
Mostly **muons** (charged, EM-interacting heavy particles, ~70%) and electrons (charged, EM-interacting, light particles, ~30%). Neutrinos are weakly interacting and can be ignored.

Rate at sea level:

~1 per minute through your fingernail

~1 per second through your open hand

~ 10,000 per sq. meter per minute

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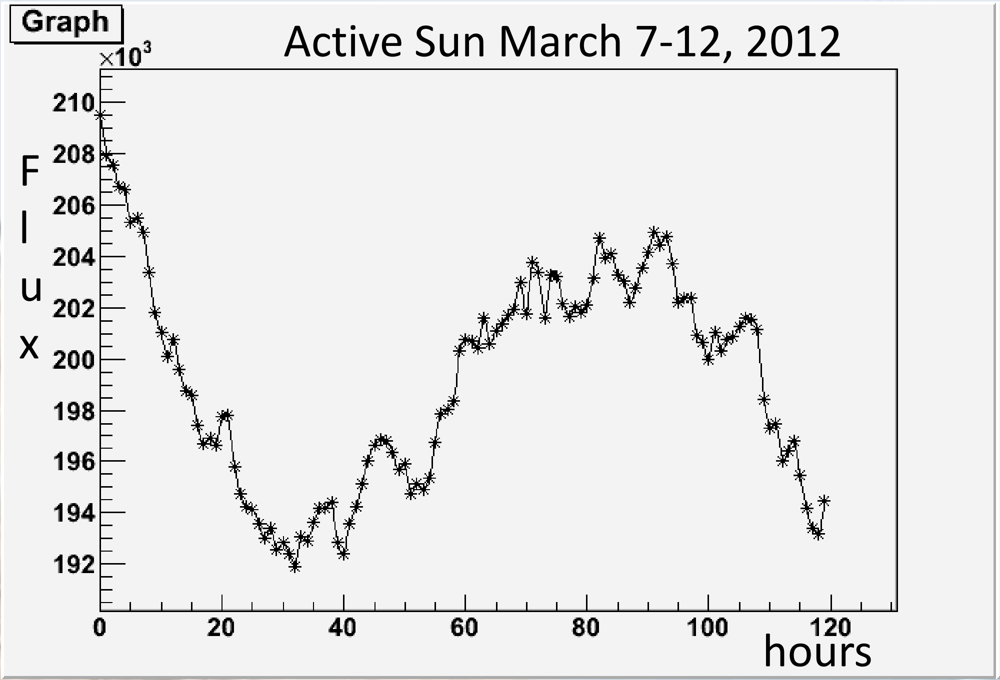
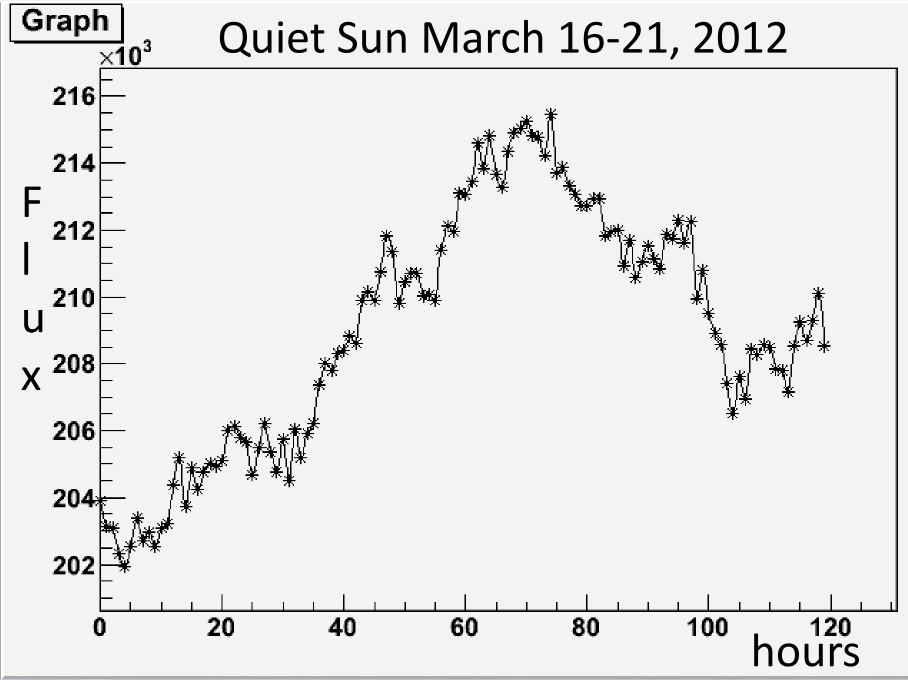
Cosmic-Ray Muon Flux Variability

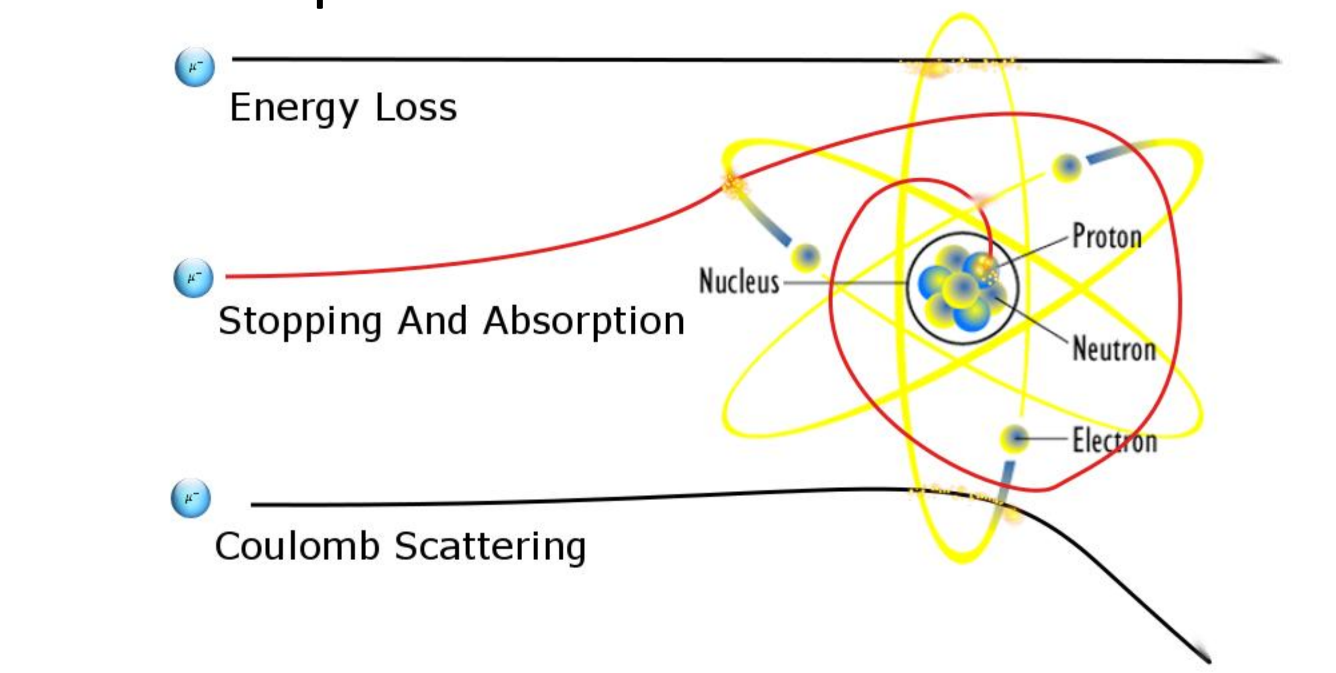




- **Variability ~10% for hourly exposures**
- **Easy to take into account or average out**
- **Is there a spectrum/flux dependence?**

Muon Interactions In Materials

- Energy loss
- Multiple scattering
- Stopping and absorption



Muon Attenuation Radiography for Large Objects

Measuring Tunnel Overburden


Commonwealth Engineer, July 1, 1955 455

Cosmic Rays Measure Overburden of Tunnel

● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lebone and Mr. O'Neill.

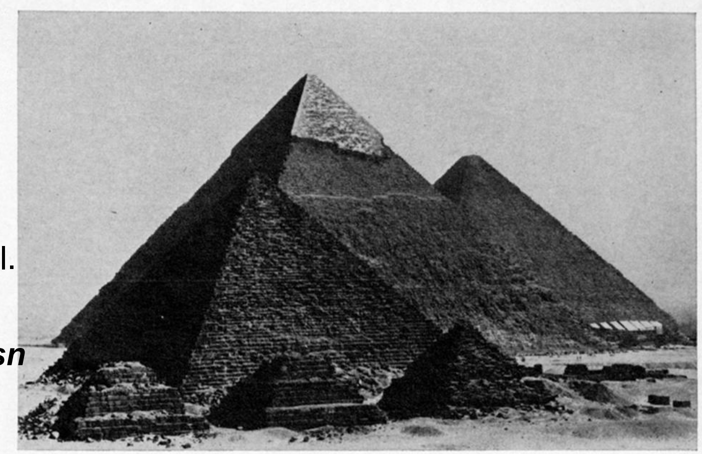
Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

By Dr. E. P. George
University of Sydney, N.S.W.

Muon attenuation radiography is known since the mid 1900s

Searching for Hidden Chambers in Pyramids

Fig. 1 (top right). The pyramids at Giza. From left to right, the Third Pyramid of Mycerinus, the Second Pyramid of Chephren, the Great Pyramid of Cheops. [© National Geographic Society]



Luis Alvarez, et. al.
Science **167**, 832 (1970)

Arturo Menchaca, et. al. current effort, see

http://www.msnbc.msn.com/id/4540266/

Predicting Volcanic Eruptions

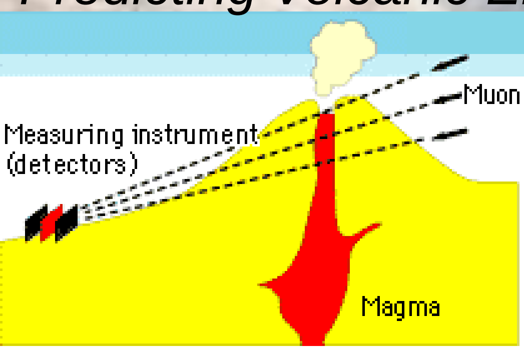


Figure 4: Analyzing the internal structure of a volcanic zone using muons

Tanaka, Nagamine, et. al.
Nuclear Instruments and Methods A **507**:3, 657 (2003)

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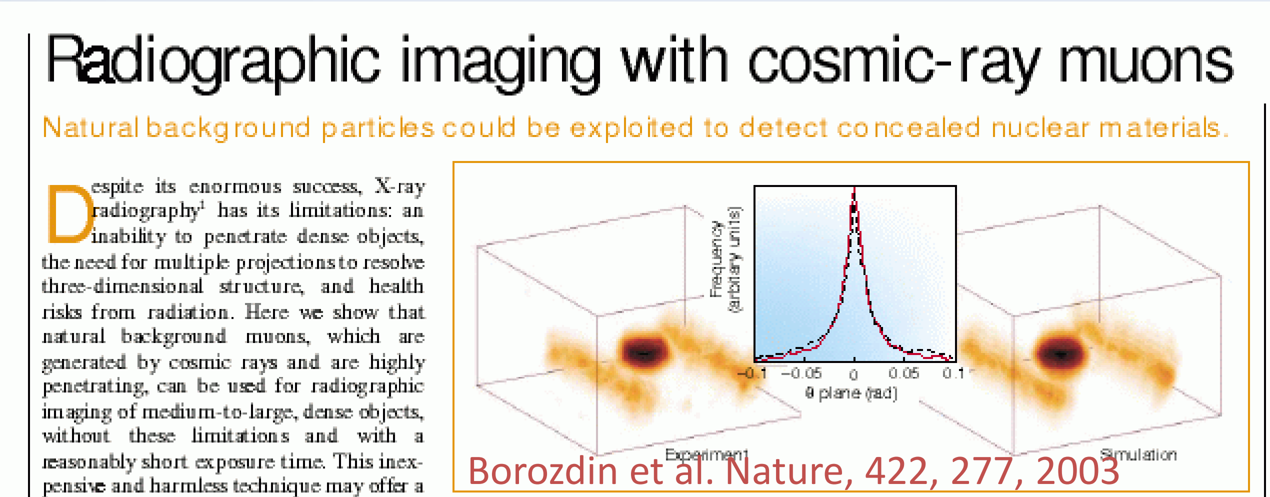
Cosmic-Ray Muon Scattering Tomography

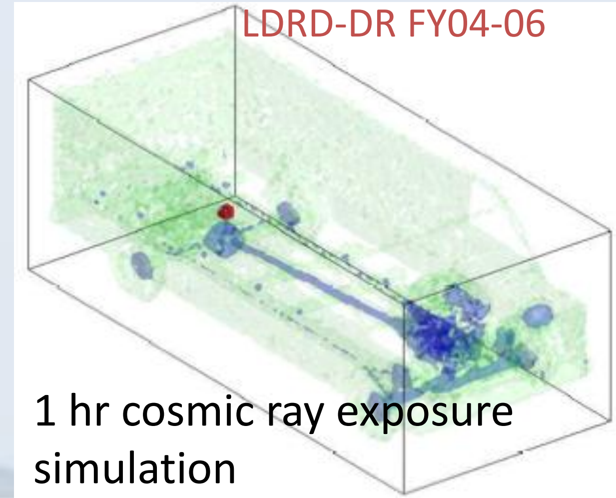


Radiographic imaging with cosmic-ray muons

Natural background particles could be exploited to detect concealed nuclear materials.

Despite its enormous success, X-ray radiography[1] has its limitations: an inability to penetrate dense objects, the need for multiple projections to resolve three-dimensional structure, and health risks from radiation. Here we show that natural background muons, which are generated by cosmic rays and are highly penetrating, can be used for radiographic imaging of medium-to-large, dense objects, without these limitations and with a reasonably short exposure time. This inexpensive and harmless technique may offer a

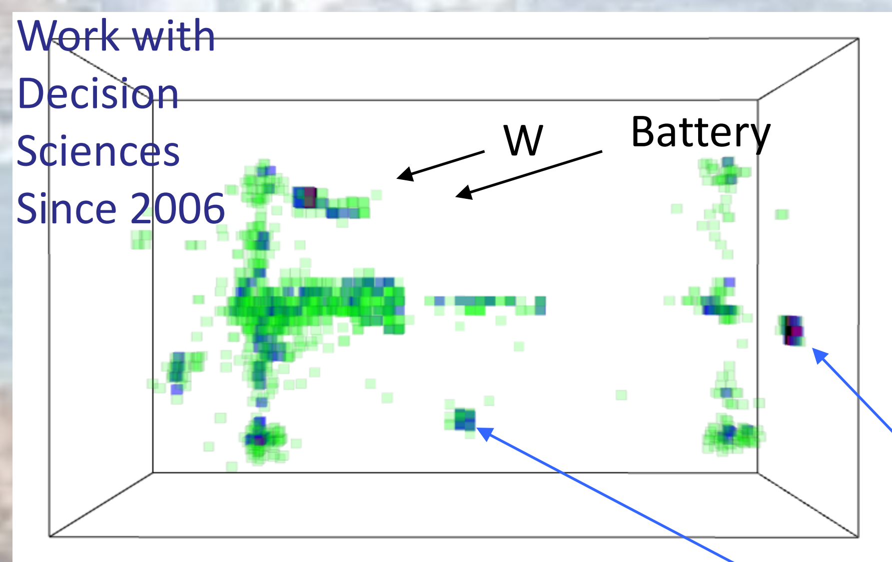
Borozdin et al. Nature, 422, 277, 2003



LDRD-DR FY04-06

1 hr cosmic ray exposure simulation

Work with Decision Sciences Since 2006



Reconstruction of Jeep with 3 objects

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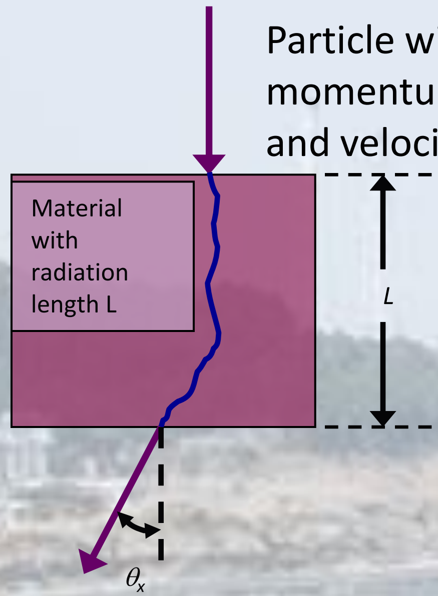
Multiple Scattering Physics

multiple scattering signal is large for high-Z, high-density objects



Particle with momentum p and velocity β

Scattering distribution is approximately Gaussian

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\frac{\theta_x^2}{2\theta_0^2}}$$

and the width of the distribution is related to the material (λ is a radiation length)

$$\theta_0 \cong \frac{14.1}{p\beta}\sqrt{\frac{L}{\lambda}}$$

Scattered particles carry information from which material may be identified.

Material	λ, cm	θ_0, mrad*
Water	36	2.3
Iron	1.76	11.1
Lead	.56	20.1
*10 cm of material, 3 Gev muons		

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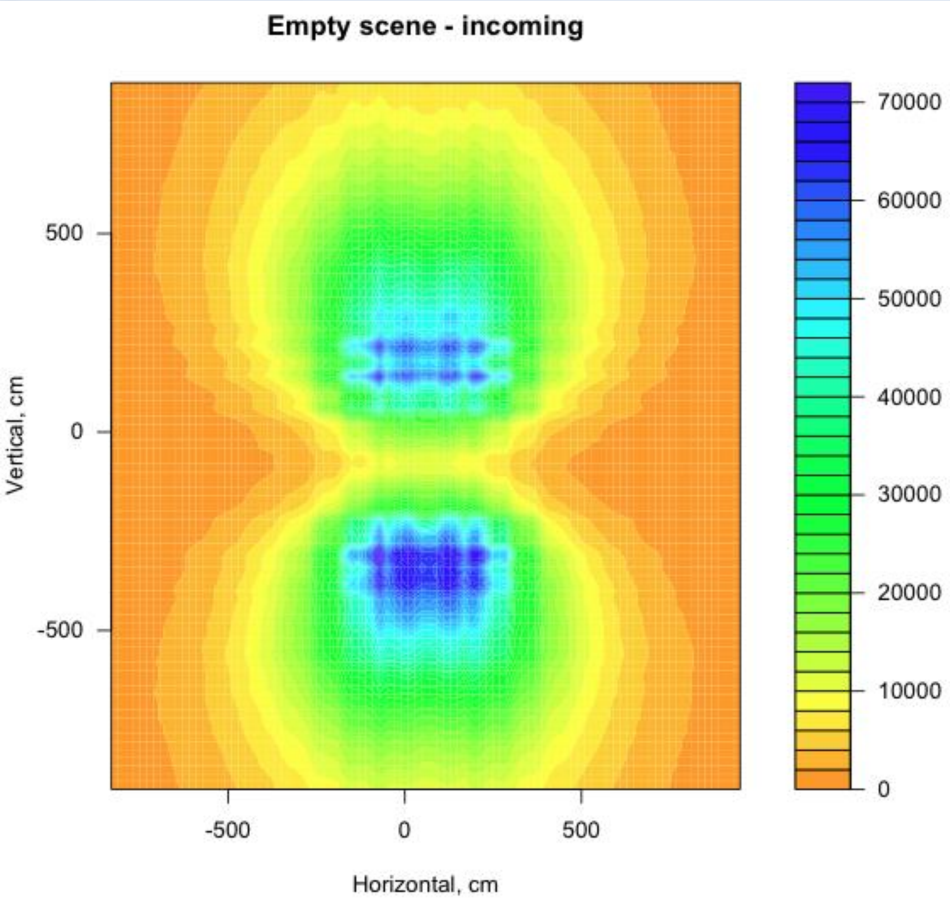
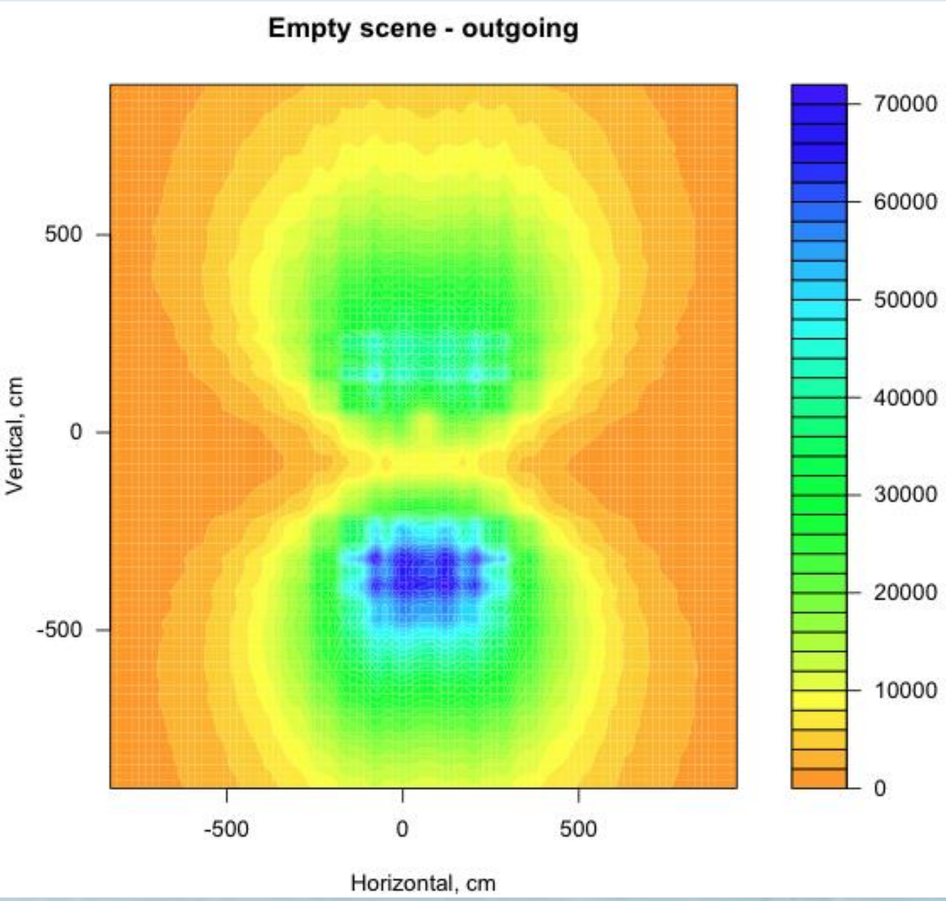
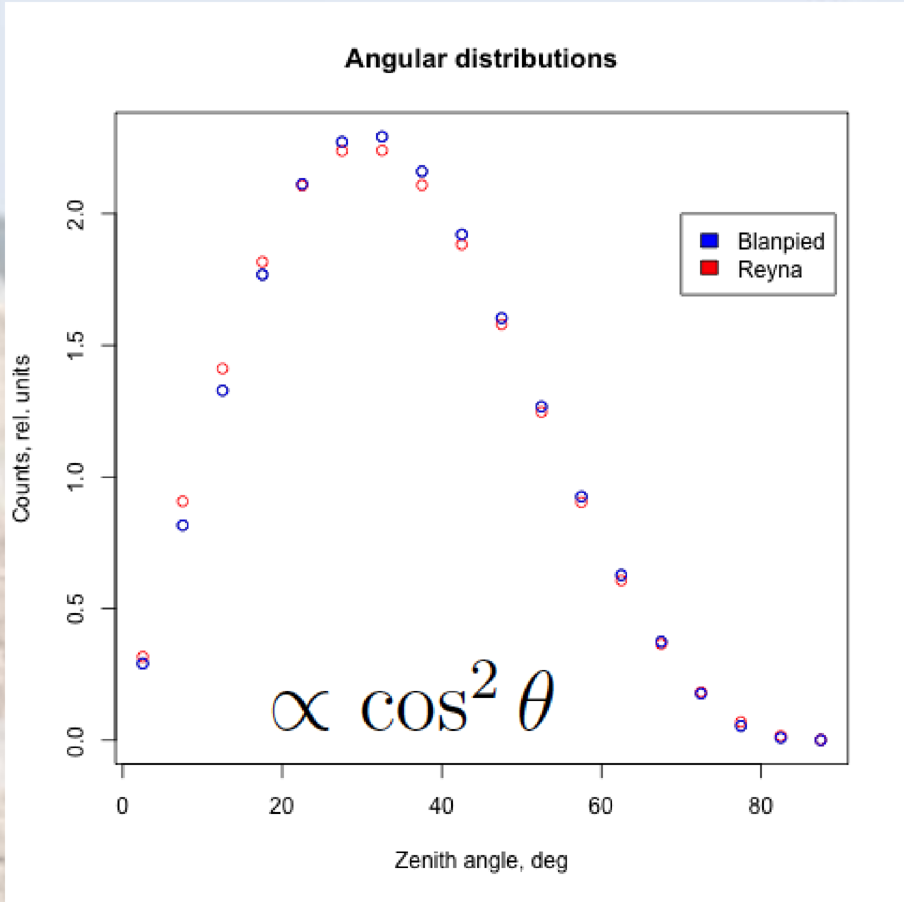
蝶 images

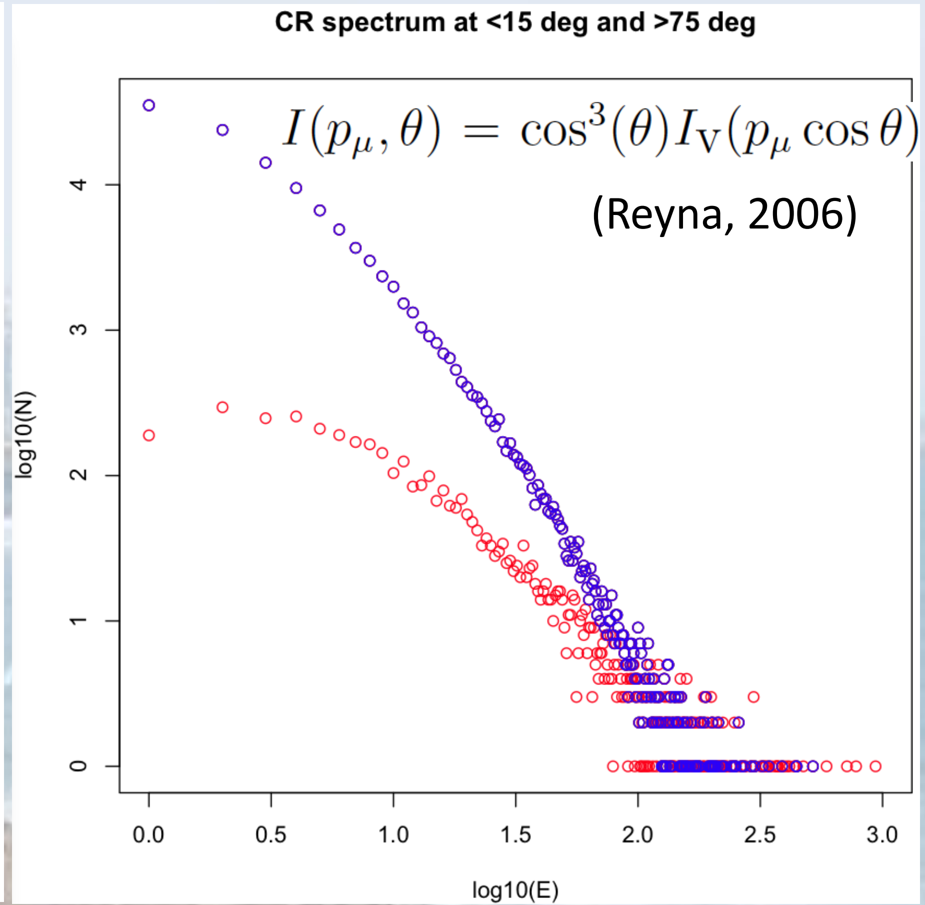




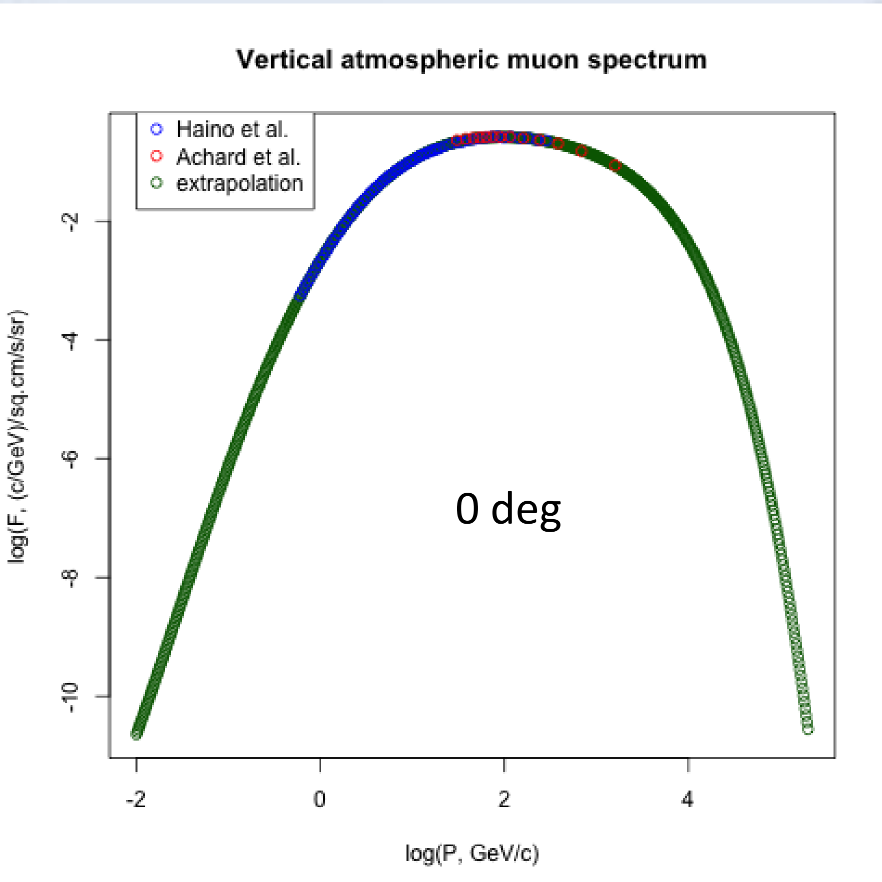
Projections to center plane: angular dependence, FOV, detector-induced structure

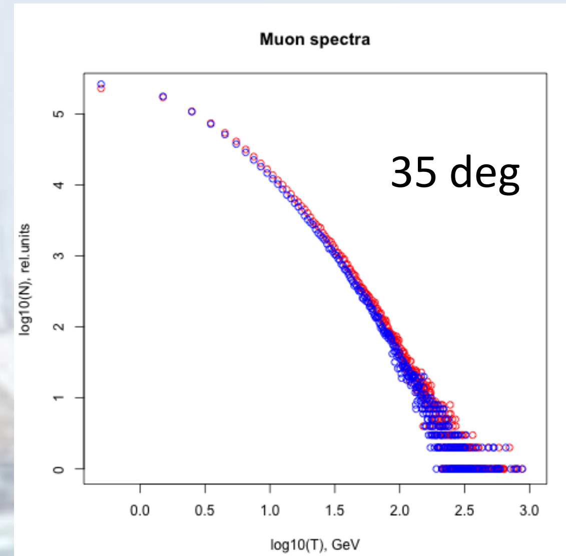
Muon flux and spectrum as a function of zenith angle

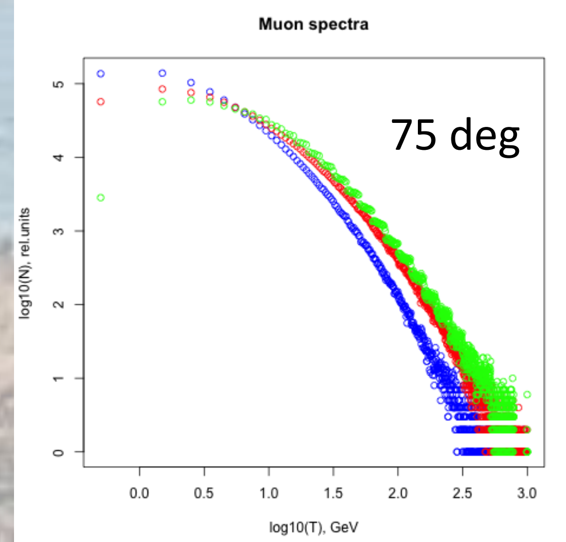




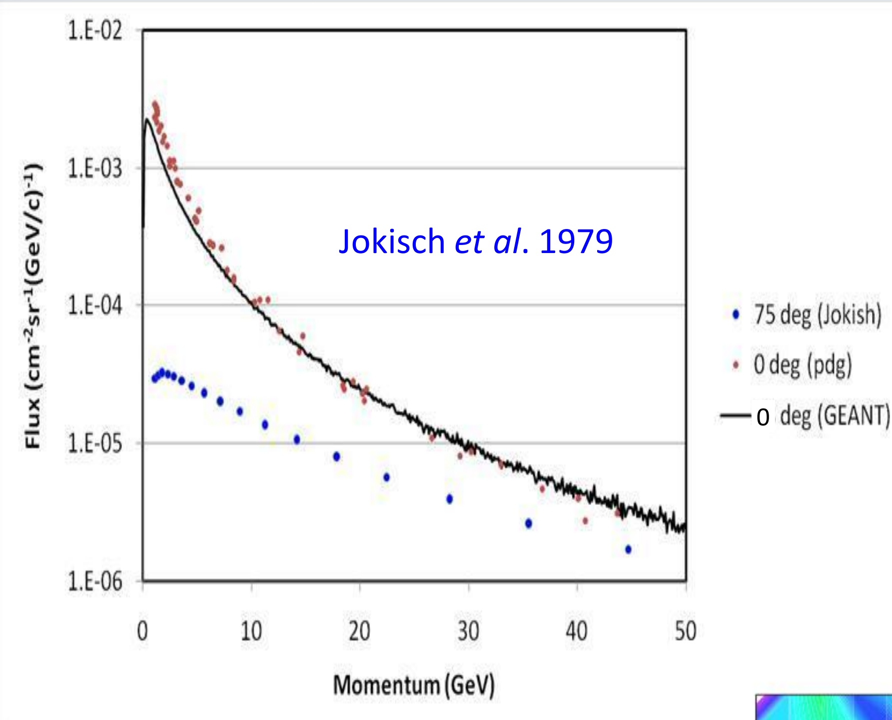
Modeling of a muon spectrum as a function of zenith angle

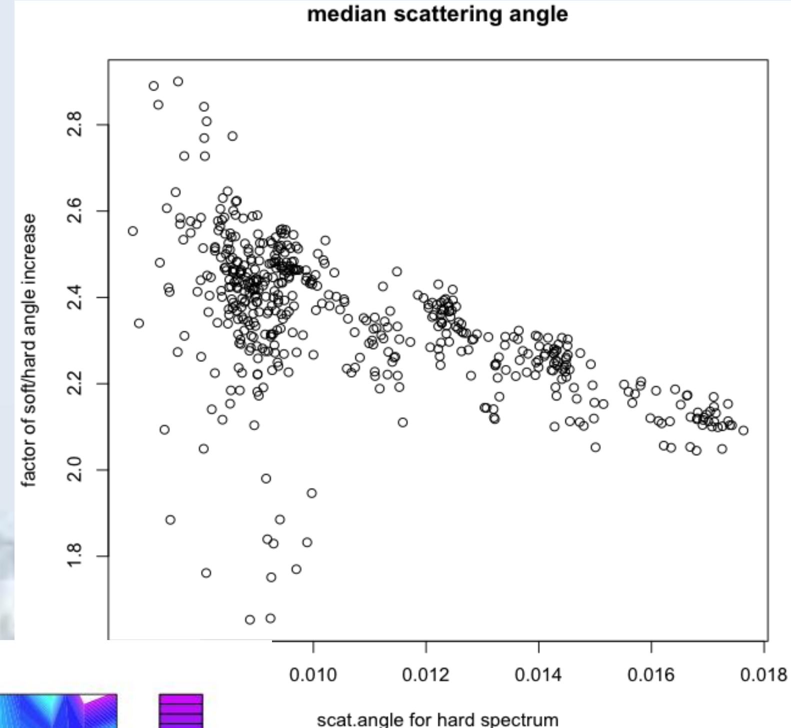


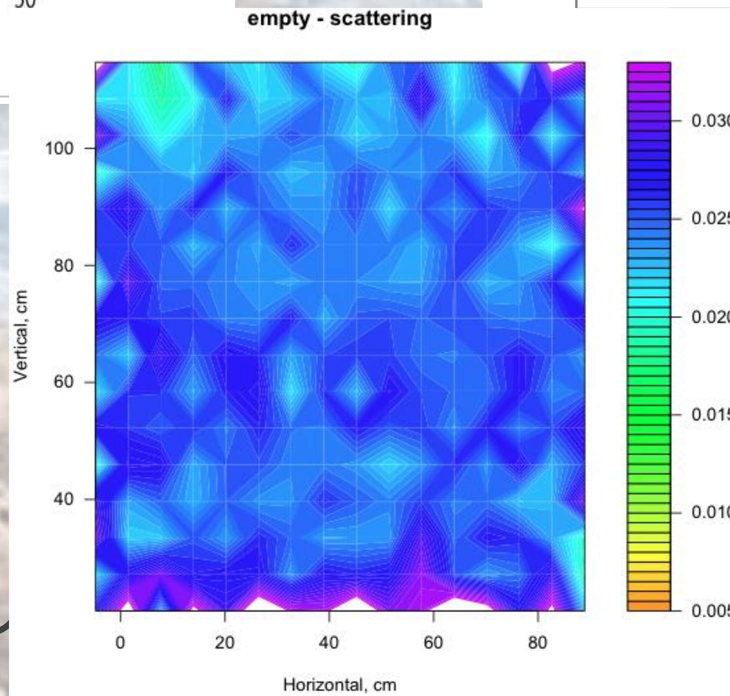




Scattering signal changes with altitude







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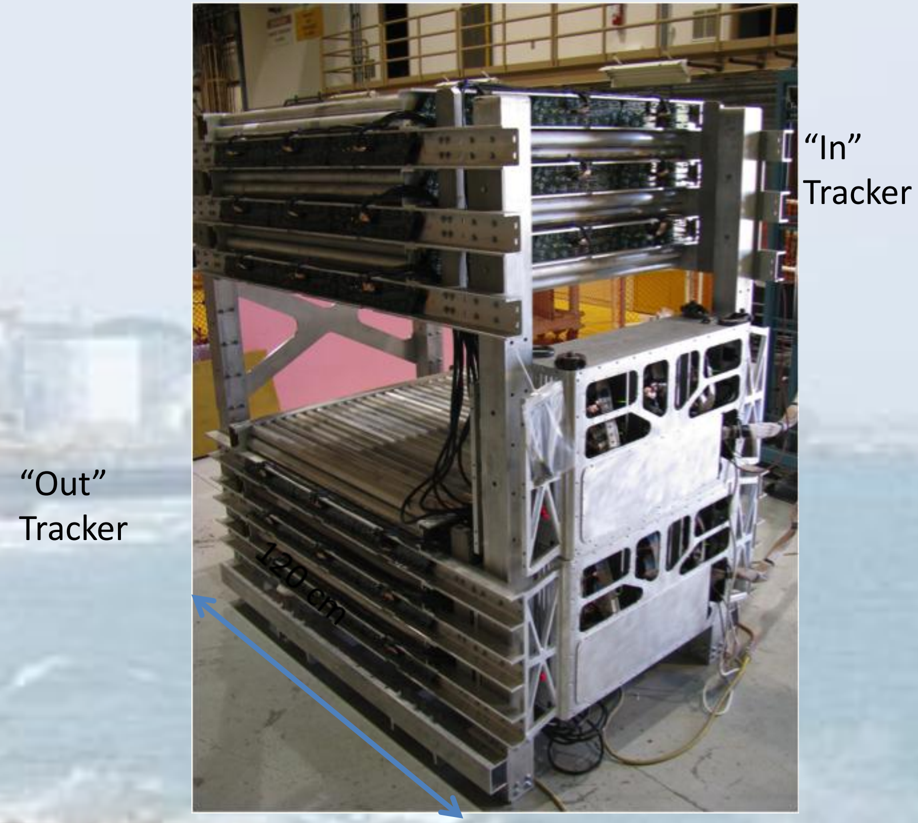
MMT – Mini Muon Tracker for Muon Tomography

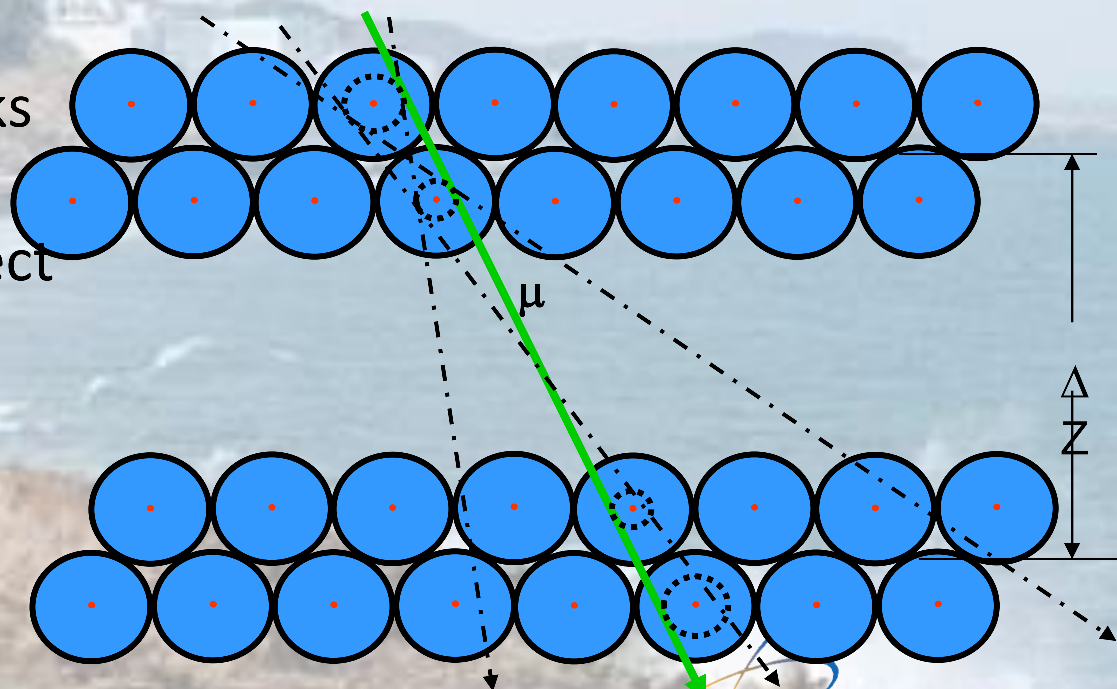
- **576 4-feet long and 2-inch thick aluminum drift tubes**
- **Each tracker set has 3 x-y pairs of double planes, for a 12-fold tracking coincidence, in and out.**
- **Tracker sets moved to “mock reactor”: one set is placed high on shielding, to track incoming muons, the other set is placed low on the “exit” side of the shielding.**



Tracking Individual Muons

- Cylindrical drift tubes measure radial position of charged particles passing through
- Yields intercept and angle in two dimensions by interleaving tubes having axis oriented in x- and y- directions

- For tomography, banks of tubes are located above and below object to measure scattering angle (average scattering density)



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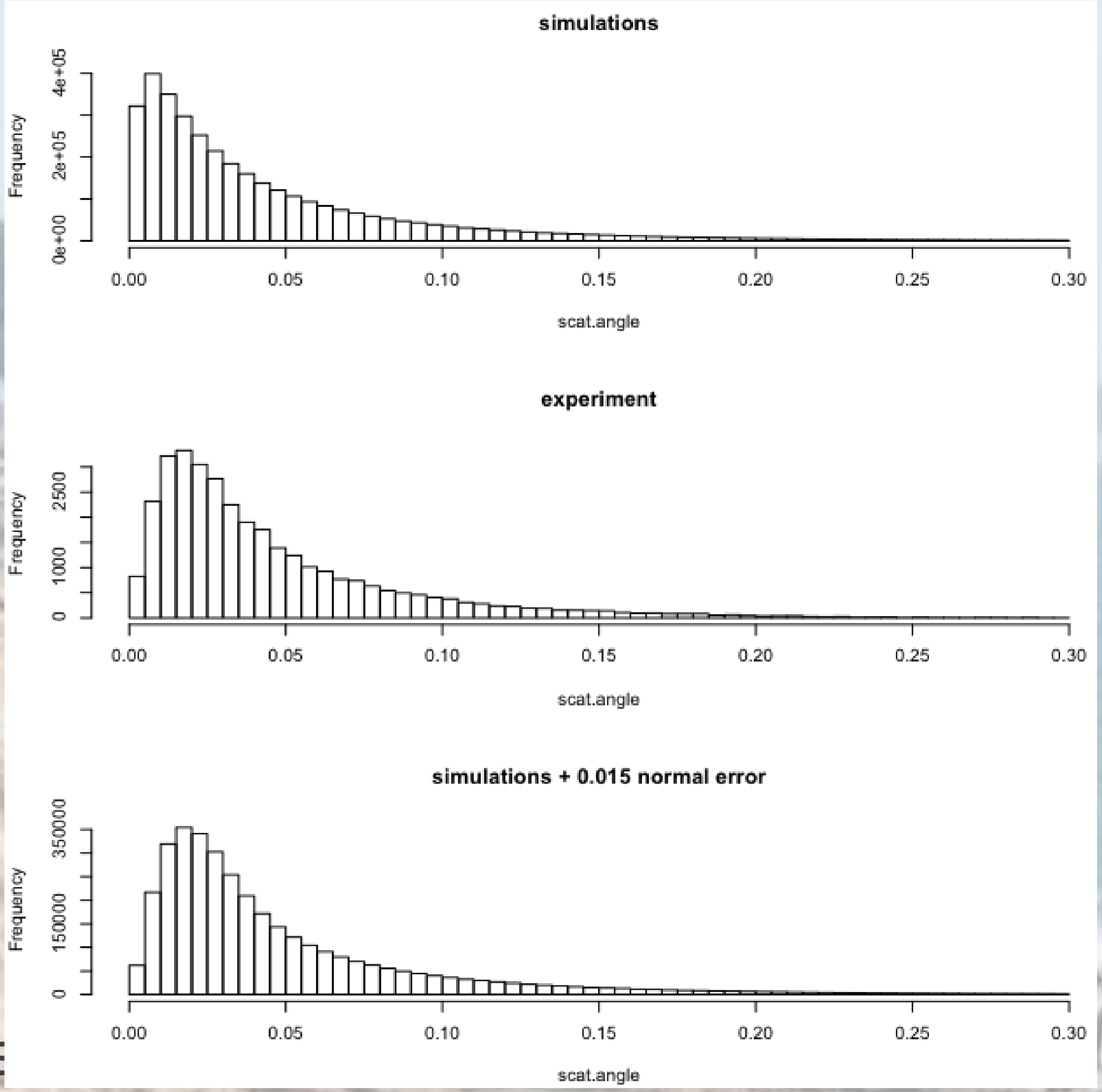
Experimental angular error can be estimated from simulations



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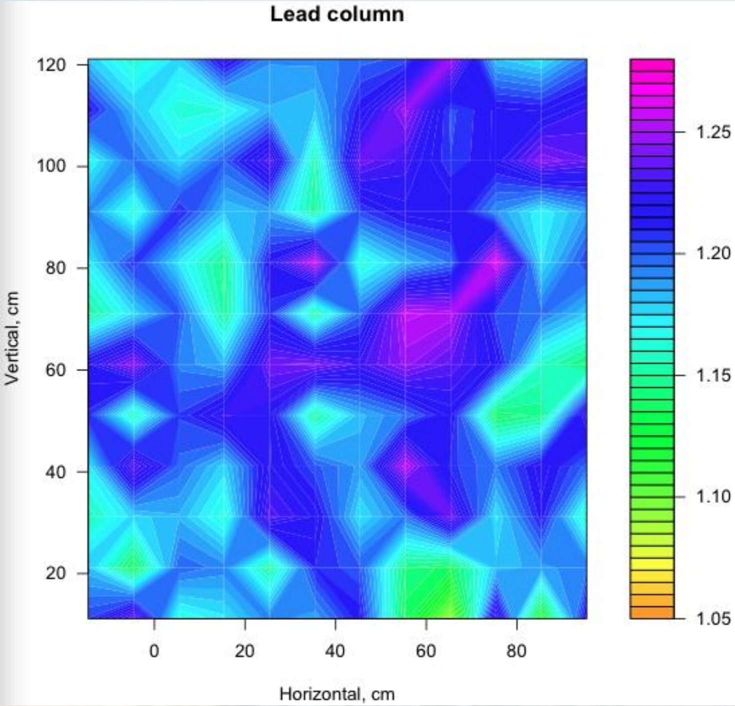
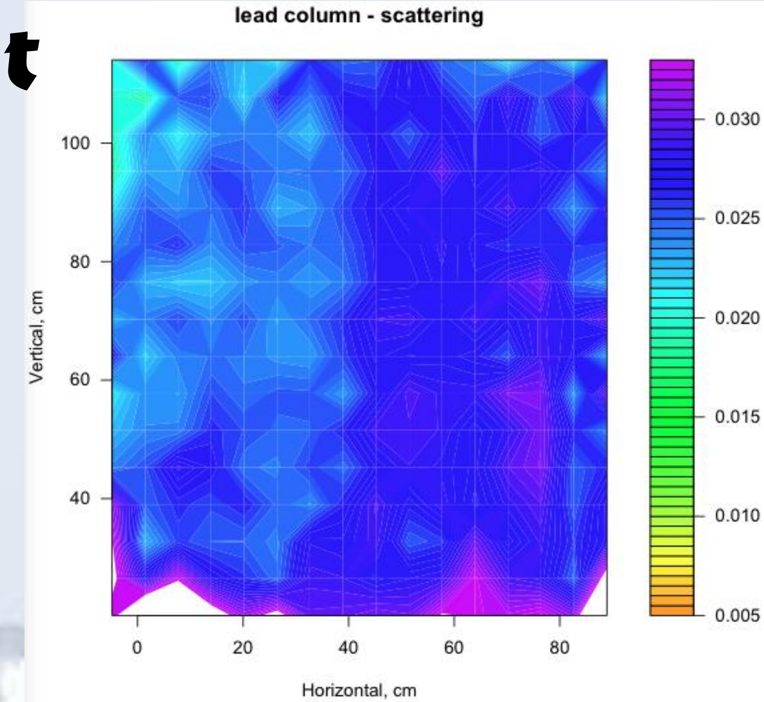
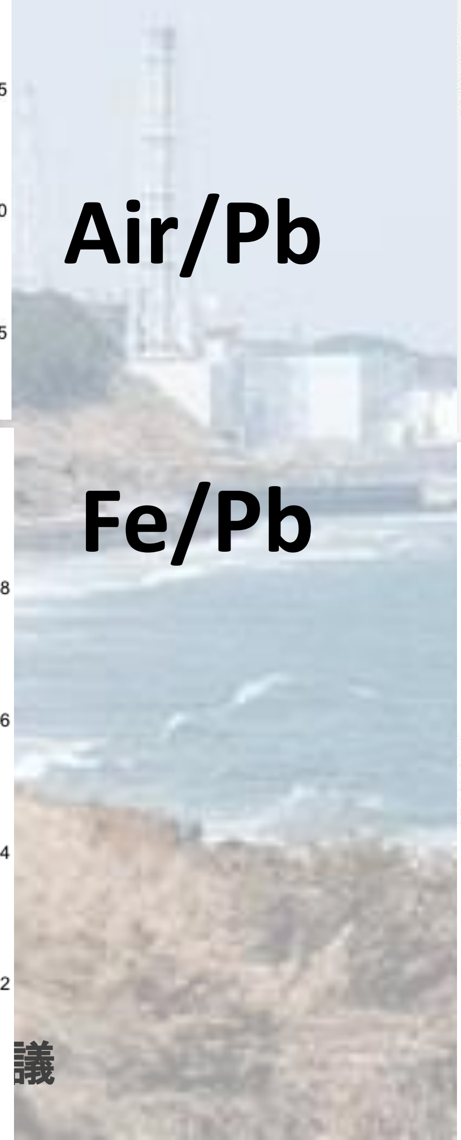
Contrast images

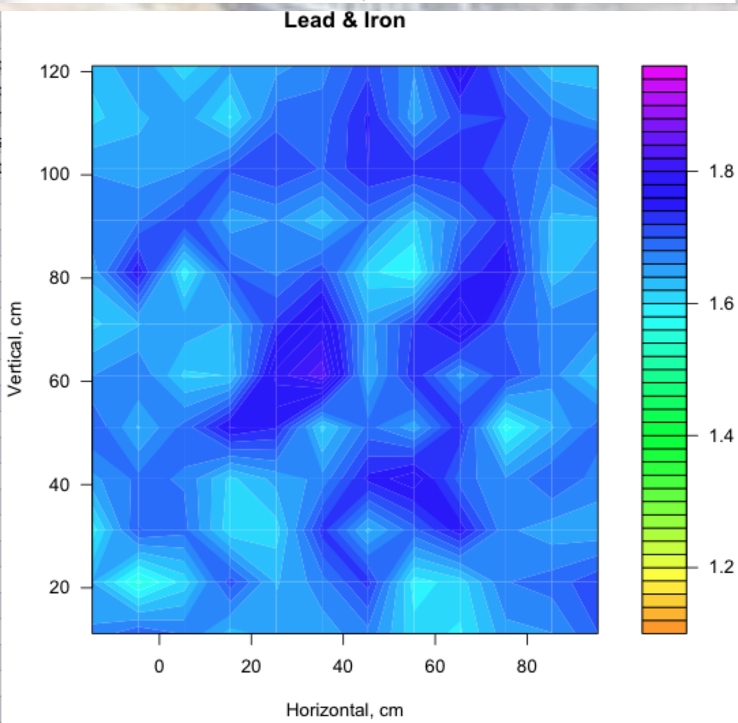


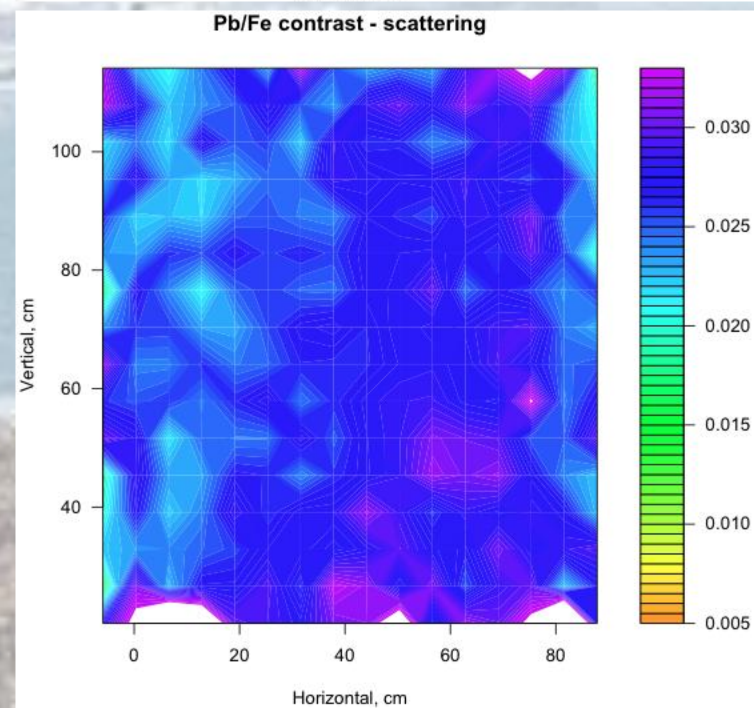


Air/Pb

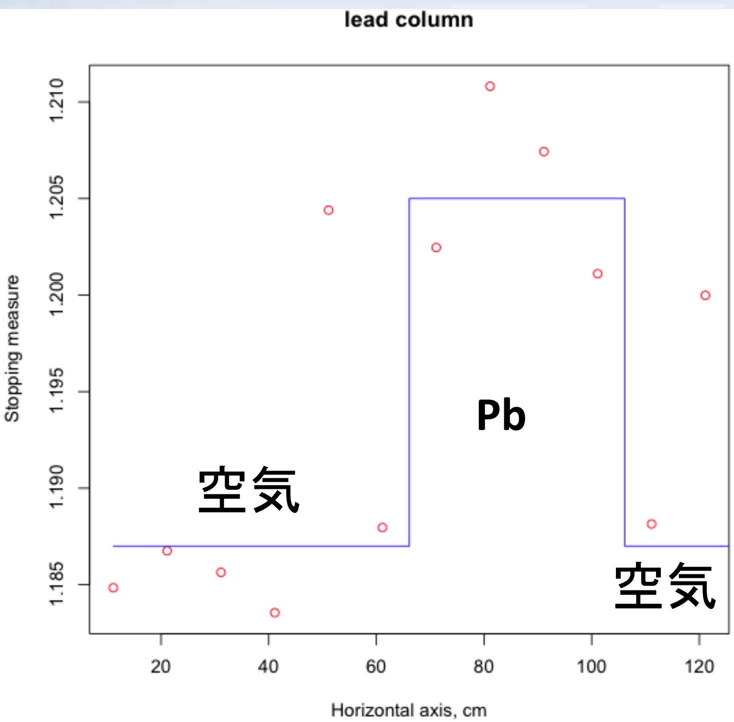


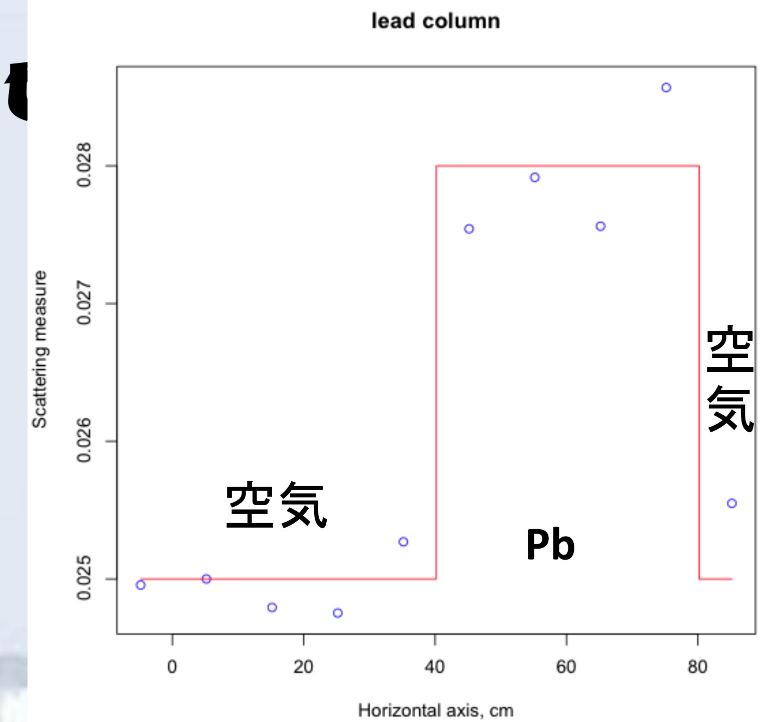
Fe/Pb

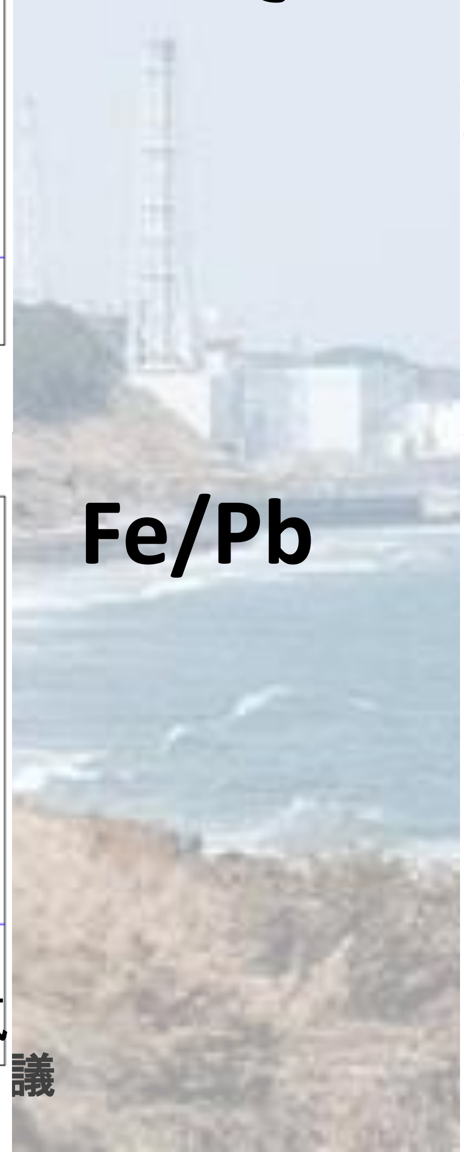




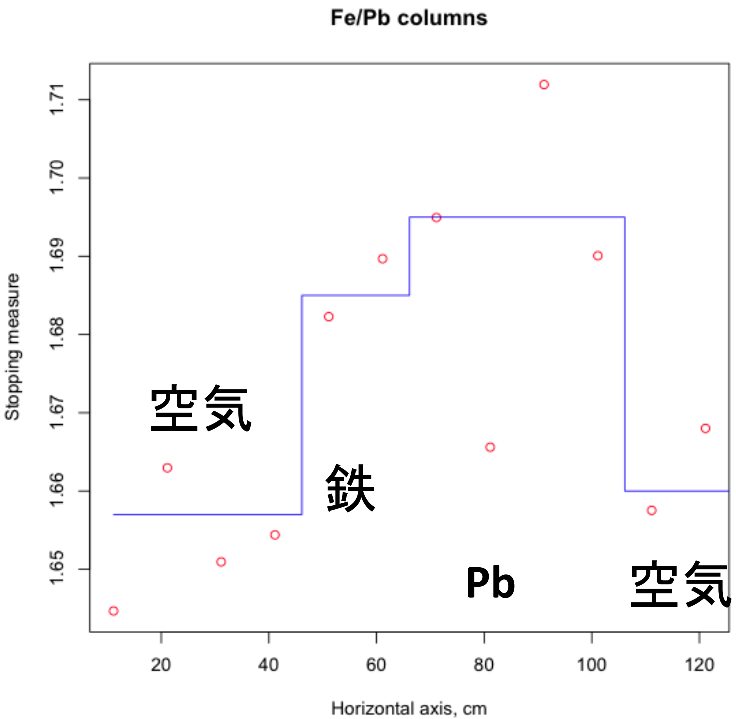
Contrast images

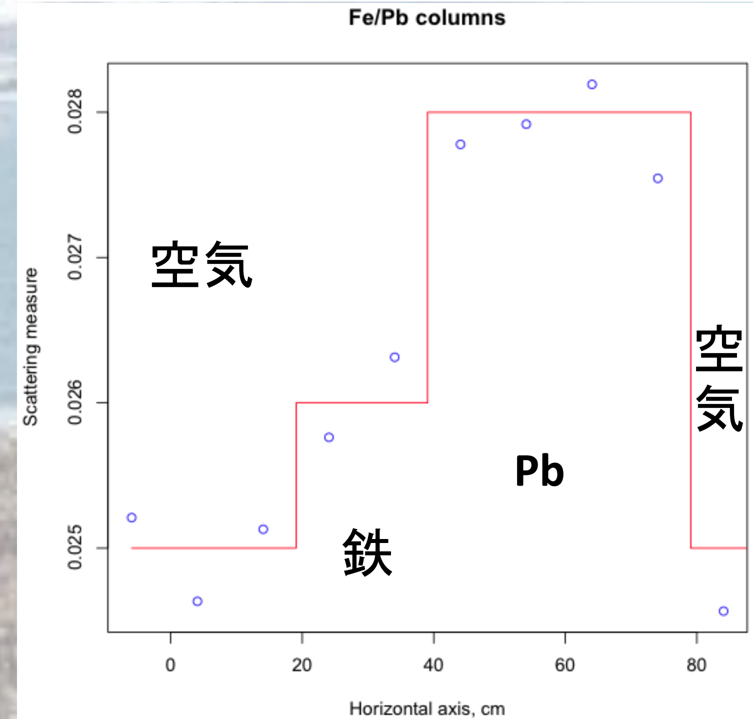






Fe/Pb





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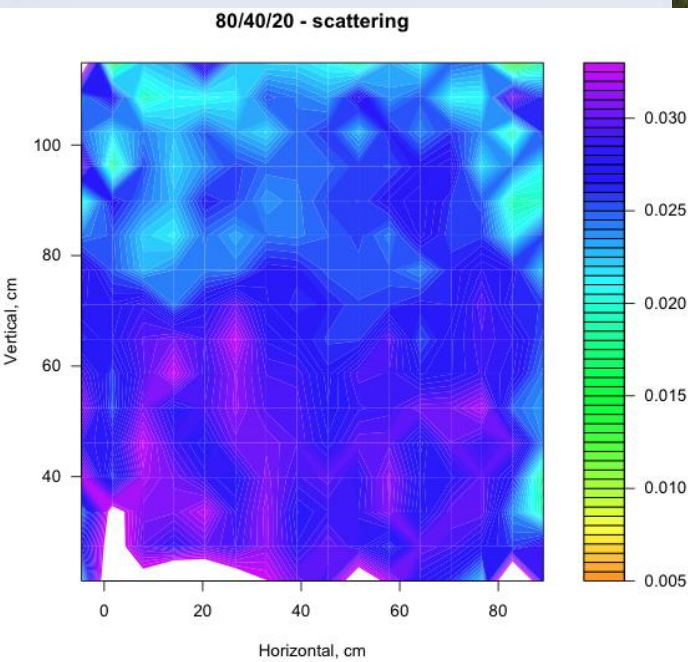
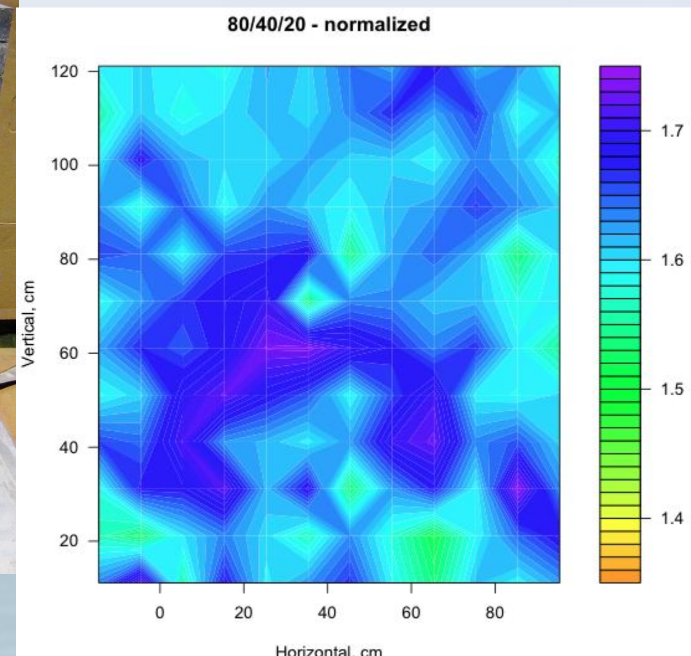
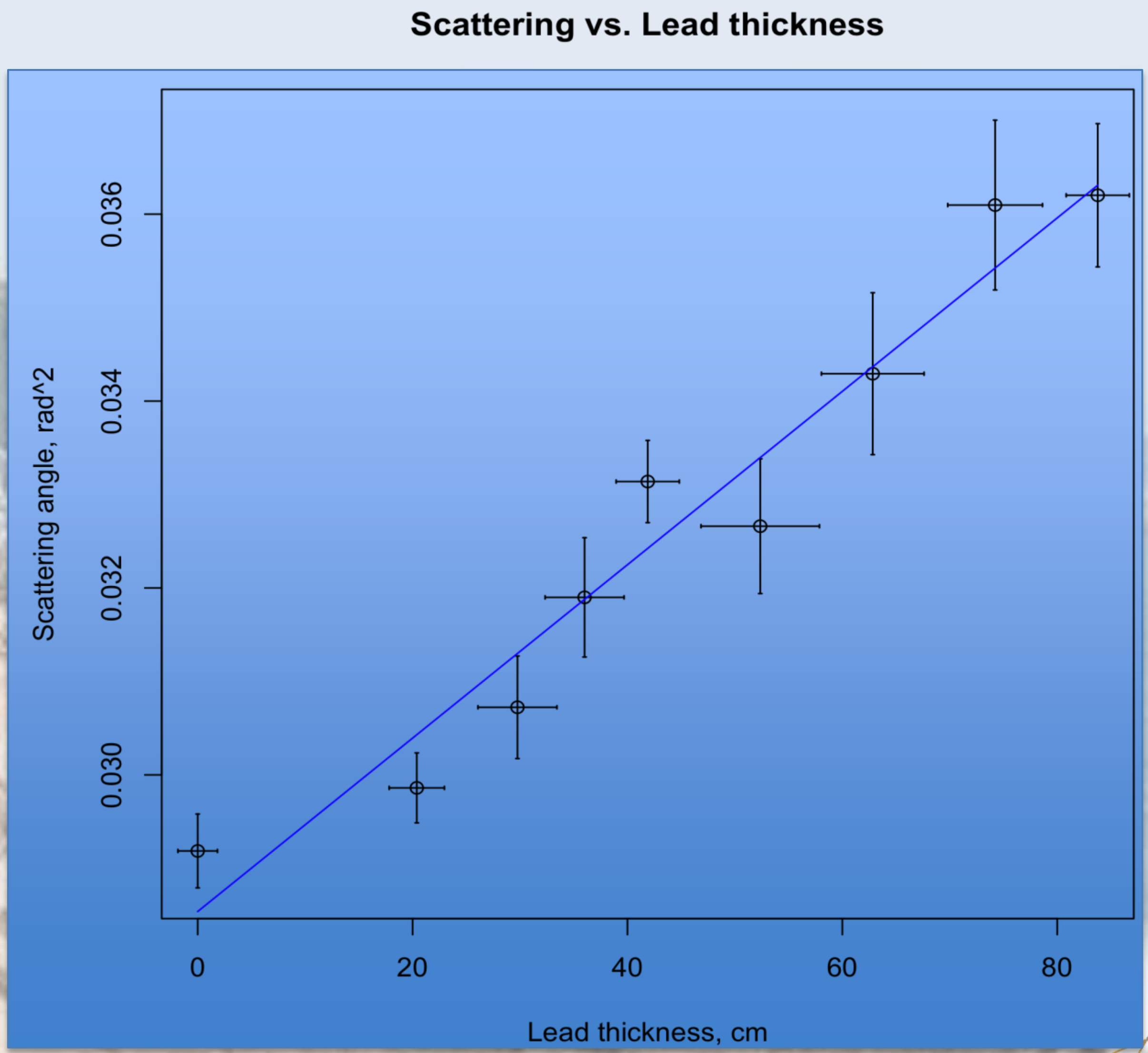
Measuring variable thickness of lead through concrete





Various thickness of lead (from 20 to 80 cm) is reconstructed in the image (8.8 days)

Scattering signal is proportional to lead thickness



Data and simulations agree

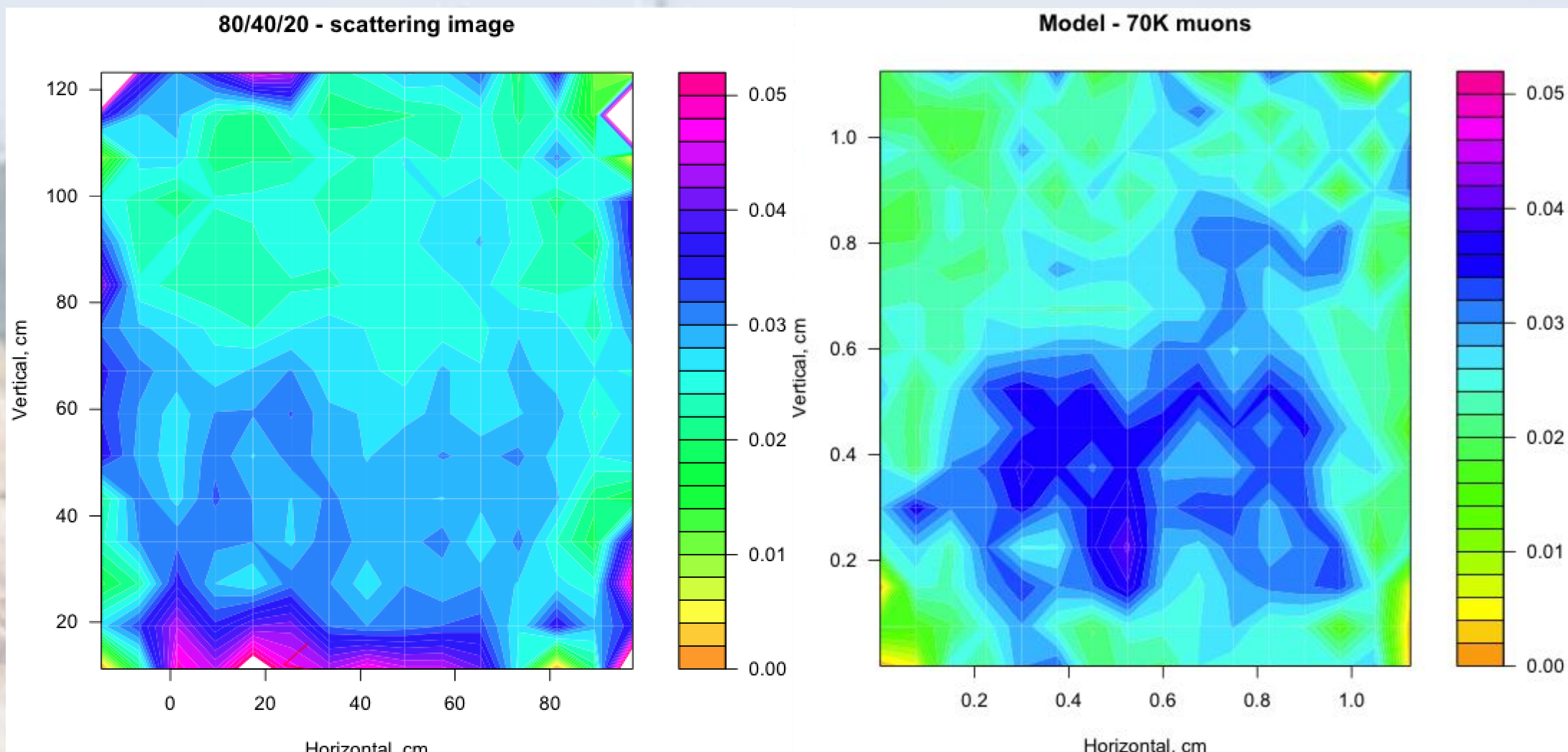
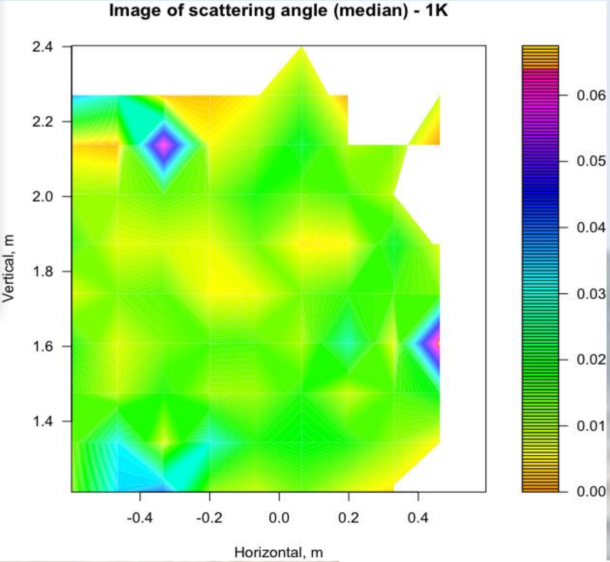
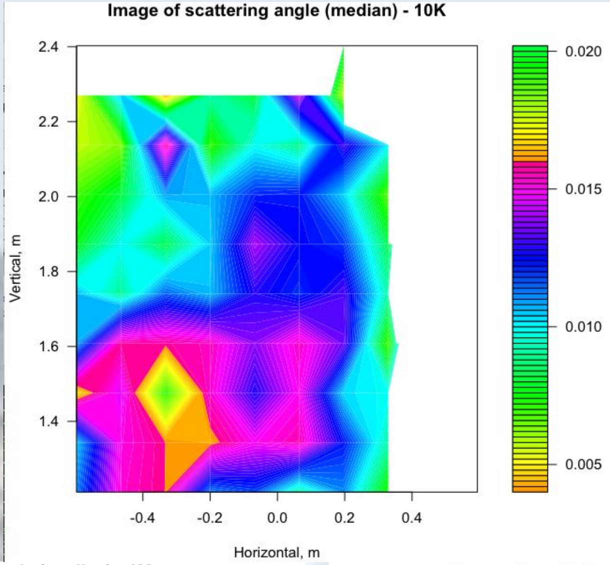
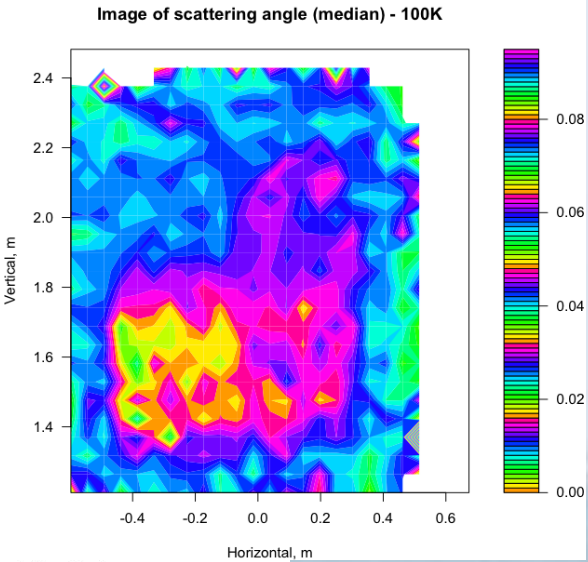
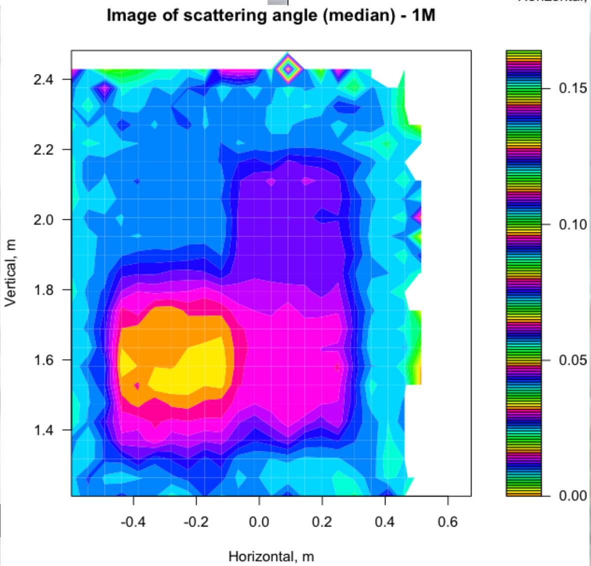


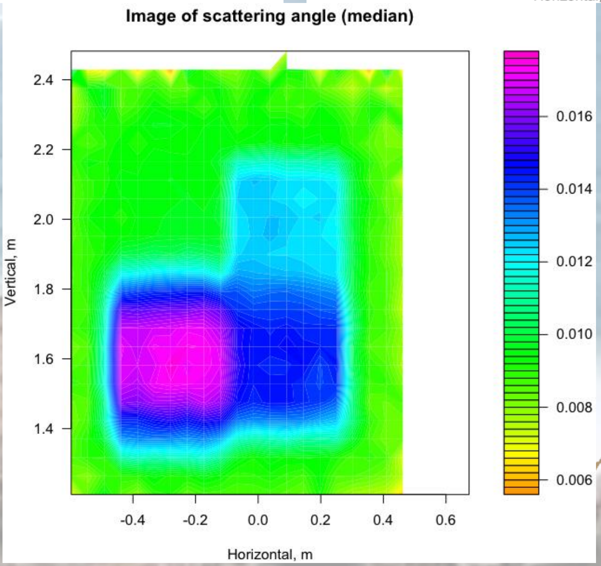
Image quality is determined by statistics



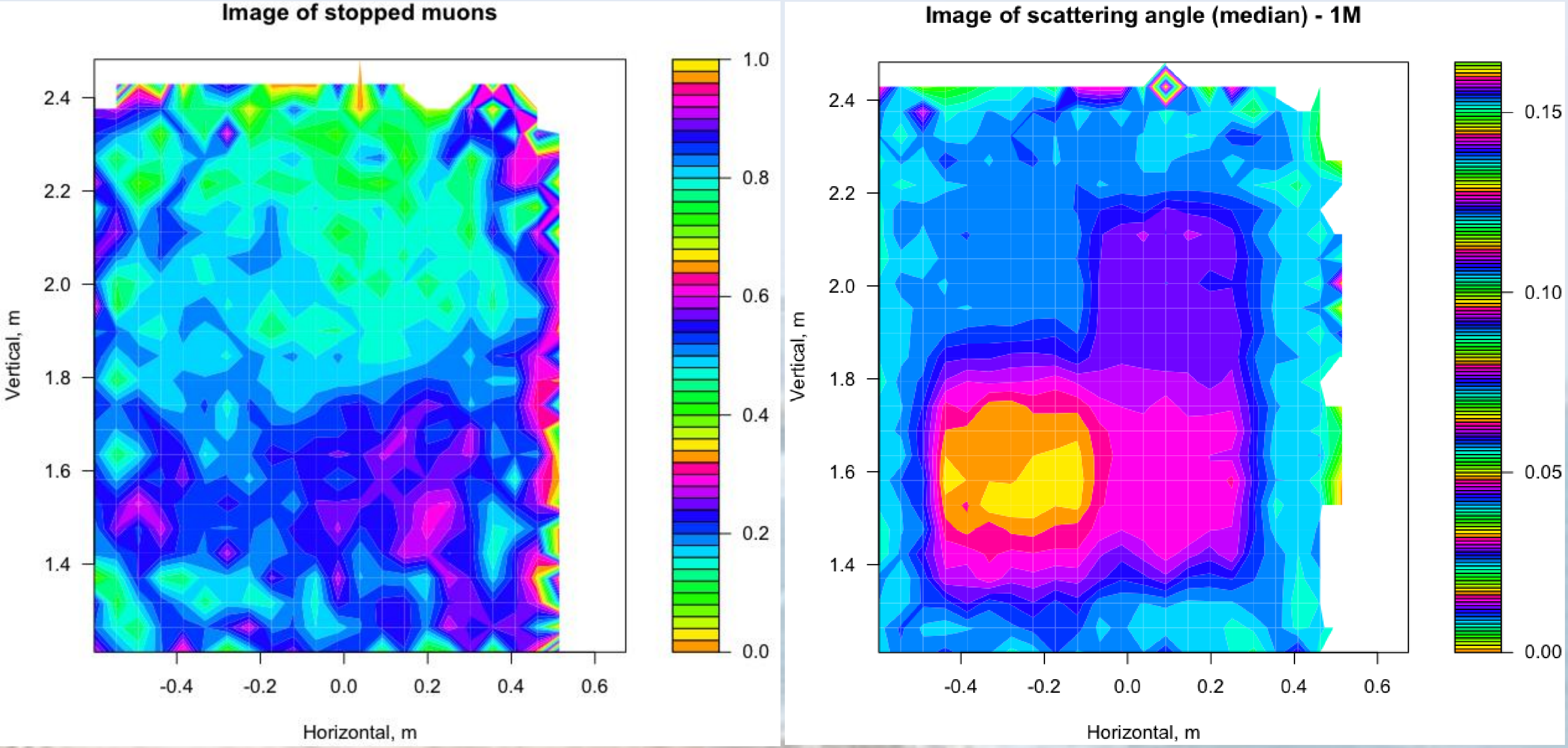








Stopping and scattering give complementary information



Both images are made from the same dataset
of 1 million muons simulated in GEANT

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Comparison of the Methods

Method	Transmission	Scattering
FOV	Limited by muon distribution B(f) ☑	Limited by the detector area ☒
Statistics	Proportional to detector area x B(f) ☑	~D_a x Ω x B(f) ☒
Resolution	Affected by: ☒ Using outgoing trajectory only ☒ Using lower energy muons ☒ Modeling incoming muons	Improved by: ☑ Using incoming trajectory ☑ Using higher energy muons ☑ Measuring incoming muons
Material Contrast	Stopping depends mostly on density ☒	Scattering depends on both density and Z ☑

Scattering method provides images of superior quality

Summary

- Cosmic Rays are studied for 100 years
- We built GEANT4 cosmic-ray generator with angular dependence of spectrum
  - How our measurements depend on the choice of cosmic ray model?
  - What is near-horizontal muon spectrum at Fukushima?
- Muon detectors are used in high-energy physics for decades
  - Momentum measurement for individual muons?
- Transmission and scattering techniques are complementary
  - How to use the information together?

Any Questions for the US Fuku Team?